PROGRESS IN THE DEVELOPMENT OF A COAL/WATER MIXTURE
AS A FUEL OIL SUBSTITUTE

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INTRODUCTION

Coal/water mixtures (CWM) provide boiler and furnace operators with the opportunity to replace natural gas or oil with coal. CWM can be pumped, stored, and atomized like a liquid fuel; thus it has advantages over pulverized coal. However, unlike natural gas or oil, coal contains significant quantities of inorganic material (ash) which can adversely influence boiler performance and fuel-handling equipment. Burners can be modified to provide satisfactory ignition and flame stability characteristics with CWM and problems associated with nozzle lifetime can be solved. However, to solve problems associated with ash, we will probably have to resort to coal beneficiation, derating, or both. Based on available data, the optimum level of coal beneficiation cannot be defined. It will be determined from trade-offs among beneficiation, burner, and boiler/furnace-related costs.

CWM is clearly outside the range of fuel parameters used to design most oil and gas-fired units. Not only are the physical properties of the fuel different, but the ash and sulfur content of CWM is at least several orders of magnitude higher than it is in most oil and gas fuels. The differences in fuel properties can cause problems in virtually every portion of the firing system/furnace. Figure 1 illustrates some of these problems, which must be addressed and solved if CWM is to be used successfully.

EFFECTS OF FUEL PROPERTIES

Fuel properties and the extent of coal cleaning will affect the potential cost of firing CWM in boilers. Fuel properties will affect:

● Ignition and stability of CWM flame

● Emission of pollutants

● Availability.

Ignition and Flame Stability

Satisfactory ignition and flame stability with adequate turndown ratio are essential to the successful use of CWM. Ignition and flame stability are related and are controlled by the aerodynamics of the flame, heat transfer in and out of the ignition zone, and fuel properties. The most important fuel property is volatility. To achieve adequate ignition and flame stability, the coal must be heated to the point where the fuel devolatilizes and ignites. Although water in

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CWM makes it more difficult to ignite than coals with less moisture, naturally occcurring coals and wood bark with up to 60-percent moisture have been successfully burned commercially.

Emissions

Many oil- and gas-fired boilers are located in areas that already have significant emissions problems. Hence steps must be taken to control particulate emissions from CWM firing which, although greater than from gas or oil, can be adequately controlled by electrostatic precipitators or bag filters.

Temperatures in CWM-fired boilers may be somewhat lower than in oil- or gas-fired boilers, tending to suppress the formation of thermal NO_x. However, fuel NO_x is temperature insensitive, and CWM will have a higher fuel nitrogen content than oil or gas. Thus NO_x emissions are expected to be higher. NO_x can be controlled by a range of techniques. Burner and combustion modifications have been successfully applied to reduce NO_x emissions when combusting coal to levels comparable to those with oil firing.

The potential for sulfur oxide (SO_x) emissions can be higher when firing CWM than for oil or gas firing. Even though most of the coals considered for CWM will be cleaned to some extent, they will be higher in sulfur than most oils. Although SO_x can be controlled by flue gas desulfurization (FGD), this technique is expensive and troublesome and is rarely used on oil-fired units. The anticipated low flame temperatures in the boiler and intimate mixing of water in CWM firing offer potential for removing sulfur compounds in the furnace by injection of calcium compounds. Furnace injection of the sorbent is much less expensive than FGD. There is an additional advantage to this approach for use with beneficiated CWM. For new, large units, Federal regulations require a 90-percent reduction of SO_x when firing high-sulfur coals. This level of removal cannot be achieved solely by sorbent injection in a boiler. However, sulfur removed during beneficiation of the coals is credited toward total sulfur removal. Therefore, if capture in the boiler can remove a significant fraction of the sulfur, the required SO_x reduction can be achieved.

Availability

Fuel properties definitely affect boiler availability. The potential problems from firing CWM in boilers designed to fire oil or gas are worse than they will be when firing it in boilers designed for coal. The cost of an inoperative 500-MWe boiler exceeds $100,000/day. The down time of an average coal-fired boiler in the United States is almost 30 days a year--at a cost of $3 million. About 60 percent of the down time is caused by boiler problems; ash characteristics--both quantity and quality of constituents--account for a significant portion of this time.

Table 1 compares parameters for gas-, oil-, and coal-fired boilers. Heat-release rates and tube-bank velocities are smaller and tube spacings in the superheater are greater in a coal-fired boiler. CWM introduces more ash, which can promote fouling, slagging, and erosion and it may contain corrosion-promoting materials.

Figure 1 shows potential problem areas where slagging and fouling can occur when firing coal in a utility-size boiler.

Table 1 Characteristics of Gas-, Oil-, and Coal-Fired Boilers

Description	Gas	Oil	Coal
Furnace Volume, Relative	1	1.3	1.9
Furnace Surface Area, Relative	1	1.3	1.7
Heat Release/Volume (10^6 Btu/h·ft^2)	25-50	25-50	10-22
Heat Release/Cooled Surface (10^6 Btu/h·ft^2)	200	200	70-120
Tube Bank Velocities (ft/s)	120	90	40-70
Superheater Spacing (in.)	2	4-6	8-16+

Difficult-to-remove slag deposits reduce heat flux through the wall, increasing furnace temperature. This deposit/temperature cycle can result in load reduction or shutdown.

As coal firing rates are increased to provide heat-release rates equivalent to those required in an oil-fired boiler, slagging may result. The higher heat-release and heat-transfer rates promote melting of particles flung to the wall above the burners. This action reduces the furnace heat extraction rate, allows higher temperatures to exist in the upper furnace, and increases the prospects of fouling the superheater. Consequently, slagging could inhibit the use of CWM in boilers designed to fire oil or gas.

TESTING

Hydraulic and burner testing have been performed at Forney Engineering Company in Addison, Texas. A test program initiated in 1981 in collaboration with a major United States CWM vendor included requirements to store, pump, transport, and burn CWM. The hydraulic test loop had typical connectors and piping, including two 10-ft sections of 1- and 2-in. Schedule 40 pipe. The test furnace is an 8-ft-dia cylindrical furnace with a water jacket. It is capable of 70 x 10^6 Btu/h for short durations and up to 40 x 10^6 Btu/h continuously. The furnace system includes a forced-draft fan with an in-line combustion air heater (gas fired), a steam generator for atomizing steam, an air compressor for atomizing air, and an ignitor system that uses No. 2 oil or natural gas. The windbox can be easily disconnected from the furnace and air duct to facilitate changing configurations.

Several pumps were tested. Diaphram and vane types were troublesome, with discharge pulsations and accumulations in the liquid end. The progressive cavity pump was the most successful but required special care during extended periods of shutdown.

Based on CWM properties, the following needs were identified for burner tip design:

● Rapid mixing of the air and fuel to dry and ignite the coal in the primary re-circulation zone.

● A strong recirculation zone maintained to create a highly radiant burning zone in the burner throat to dry the coal.

● No flame contact on any burner part because of anticipated slagging problems.

● Conventional burner parts for ease in retrofit applications.

Forney has several commercial burner designs for various applications:

● Parallel Air Flow (PAF)

  – Fast mixing

  – Low excess air applications

● Rotating Air Register (RAR):
  Highly turbulent

● Variable Flame Pattern (VFP): Variation of PAF with flame-shaping ability with rotational secondary air register.

Historically, Y-jet (YJ) and internal mix (IM) atomizers had been success-fully used with high-gravity fuels. We attempted to adopt the basic features of each in two different atomizer designs--both incorporating a conical plug rather than individual orifices. Concepts for both atomizer tips, shown in Figure 2, have been patented.

After a matrix of tests including YJ and IM atomizers in RAR and VFP air registers, the following requirements were noted:

● Burner with two airflow paths with the primary path having a rotational, low flow

● Secondary airflow with high swirl to provide the recirculation zone

● Means of providing a highly radiant zone at burner exit.

These considerations were included in the design shown in Figure 3. This patented design provides dual velocities and two-throat configuration to maintain a radiant zone at the burner exit. A series of tests were successfully conducted under the usual burner performance parameters.

BOILER DESIGN VS. CONVERSION POTENTIAL

Designs of existing utility steam generators vary substantially depending upon the original design fuel. Generally, the pressure-part arrangement of a boiler can be classified as one of the following types:

- Category A Unit--Two pass (Coal/Oil-Gas)

- Category B Unit--Two pass (Oil/Gas)

- Category C Unit-- Box type (Oil/Gas or Gas only).

The design configuration of each type of unit greatly affects its conversion potential in terms of both capital expenditure and derating requirements. Figure 4 shows a comparison of unit configurations that will be discussed.

Category A Unit-- Two Pass (Coal/Oil-Gas)

Design Features. This type unit is characterized by a generously sized furnace (i.e., large plan area and a substantial distance from the burner zone to the first vertical radiant surface at the furnace exit). These features result in a sufficient radiant absorption in the furnace area, which lowers the furnace exit gas temperature entering the vertical convection sections, thus limiting slag formation. Also typical of this type of unit is a lower furnace hopper slope of at least 45 to 50 deg and a hopper throat opening of approximately 3 to 4 ft, both of which facilitate bottom ash collection and removal. The horizontal convection passes of a Category A steam generator are designed with adequate tube-to-tube clear spacing to prohibit fouling and possible plugging and to alleviate excessive flue gas velocities and associated tube erosion possibilities.

Conversion Potential. This type of unit was originally intended for burning coal as its primary fuel. Therefore, it should achieve full load output if reconverted to a similar type of coal or a CWM. The capital expense of the boiler portion of the conversion would be limited to refurbishment of original equipment, normal maintenance, and pollution control upgrading, if required.

Category B Unit-- Two Pass (Oil/Gas)

Design Features. The Category B classification includes those steam generators with a furnace configuration similar to that of a Category A unit but with a less conservative convection pass arrangement. This type of unit was originally designed for oil or gas firing. The similarities in furnace arrangement when compared with the unit previously discussed are readily apparent. Generally, the furnace of a Category B steam generator is smaller than that of a Category A steam generator. Specifically, the former has a lower furnace hopper slope and opening and the furnace plan area is not as conservative. However, the overall furnace design for this type of unit is conducive to the firing of an ash-laden fuel. For this reason, based solely on furnace design criteria, a Category B unit is a viable candidate for conversion to pulverized-coal or CWM firing with minimal or no unit derating.

However, the convection pass arrangement in this unit can present several major obstacles when converting to coal or a coal-derived fuel. The clear spacings between tube sections of a Category B unit are less than those of a Category A unit. If such a unit were to fire coal or a coal-derived fuel, excessive fouling or erosion of the tubes could result, since the flue gas temperature and velocity of the unit would exceed the acceptable values for oil firing. To decrease flue gas temperatures and velocities so that the potential for fouling or erosion of existing convection pass tube banks can be reduced, the maximum unit load must be restricted. These design constraints are directly related to the fuel being considered, particularly the quantity and quality of its ash. Therefore, as might be expected, the derating requirements for coal and CWM vary.

Conversion Potential--Coal. Coal inherently has the highest ash content of the fuels being considered and will also exhibit the highest furnace exit gas temperature for any particular boiler load and furnace size. Consequently, the potential for convection pass fouling and tube erosion can restrict the maximum allowable output to approximately 70 percent of the design rating of a Category B Unit. This derating requirement can often be minimized or eliminated through substantial pressure-part modification. As indicated previously, the furnace of such a unit is normally capable of supporting full output while firing coal, and thus modifications to the furnace (which would be prohibitively expensive) would generally not be required.

Conversion Potential--CWM. Because of the ash and sulfur reductions that occur during the fuel preparation process, a Category B unit can be converted to CWM firing with less derating than would be required with coal. Reductions in ash (approximately 70 to 90 percent) and sulfur (50 to 70 percent) are possible during CWM beneficiation. Furthermore, the ash fusion temperatures of a beneficiated CWM are 100 to 200°F higher than those of the parent coal.

Consequently, higher furnace exit gas temperatures are allowable when firing CWM as opposed to coal. In a Category B boiler, higher temperatures translate to an allowable load of approximately 80 to 90 percent of full unit output. Again, convection pass pressure-part modifications could possibly restore such a unit to full load capability while firing a CWM.

Category C Unit--Box Type (Oil/Gas or Gas Only)

A Category C unit could be subject to a considerable derating if converted to coal or CWM. The horizontal convection passes of such a unit have closer tube-to-tubeside spacings than those of either Categories A or B boilers. The most critical disparity lies in the furnace design. A Category C unit has little or no provision for ash collection or removal, and the furnace is inadequately sized to reduce the potential for slagging associated with coal firing. The hopper slope is very shallow (or nonexistent), and the lower furnace throat opening (if any) is minimal. Burner spacings are generally close, and the distance from the lowest burner level to the hopper knuckle (or to the furnace floor) is generally inadequate. Both of these features result in a high furnace slagging potential. However, the most critical design limitation in evaluating the conversion of a Category C unit to firing coal or a coal-derived fuel is the inadequate furnace plan area. Modifications to the furnace hopper and burner pattern in many cases prove feasible and can minimize derating. This is also often the case with respacing of the convection passes, as was indicated in the previous discussion concerning a Category B unit.

However, furnace plan area enlargement is not feasible either physically or economically. Thus the derating for a Category C unit is more severe than that associated with the previously discussed boiler designs. Moreover, pressure-part modifications, within the realm of technical and economic feasibility, cannot alleviate these load restrictions.

Conversion Potential. Typically, conversion of a Category C unit to firing pulverized coal would involve a derating to 50 to 60 percent of design output because of furnace and convection pass design limitations previously identified. CWM presents the better conversion alternative for a Category C unit. Because of the ash and sulfur reduction that occurs during the fuel preparation process, slagging and fouling potential is considerably reduced. Even so, unit output may be restricted to approximately 70 to 80 percent of design rating.

Table 2 presents a summary of the typical feasible unit deratings for coal and CWM and for each type boiler.

Table 2 Maximum Allowable Load, %

Fuel	Category		
	A	B	C
Coal	100	70	50 - 60
CWM	100	80 - 90	70 - 80

Balance-of-Plant Considerations

The utilization of either coal or CWM in a boiler fuel conversion project significantly affects the required balance-of-plant equipment, impacting both the capital cost of the conversion and the site requirements. Each of the fuels studied has been examined in terms of the balance-of-plant considerations arising from a potential conversion project. The scope and costs of such equipment vary, depending on the original design fuel for each specific unit.

Balance-of-plant considerations must, at the very least, include:

• Refurbishment of coal-handling equipment (if it exists)

• Fuel handling

• Land requirements (coal yard and ash disposal)

• Fan systems

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- Ash collection, storage, and removal systems

- Fly ash collection

- FGD system.

Compared with total plant conversion costs, boiler/island-related work is approximately 10 to 20 percent of the total project cost. However, the steam generator remains the primary consideration for potential derating.

ECONOMICS OF CONVERSION

An evaluation of the capital expenses vs. the fuel savings of a potential conversion project is unique to the steam generator under consideration. Some general observations regarding the effect of basic unit design criteria and site considerations have been discussed. Such generalities are not possible regarding the specific economics of a conversion. To provide an indication of these economics, a specific unit has been selected as a test case for comparison of conversion to coal or CWM. The analysis is specific to that unit but the methods will be common to any conversion project.

The selected Category B steam generator is a natural-circulation, balanced-draft, reheat unit utilizing a parallel pass gas flow arrangement. The unit, originally designed to fire oil as the primary fuel, could be converted to coal firing in the future, because of the relatively large furnace plan area, the lack of lower furnace radiant superheater surface, and the presence of a lower furnace hopper with an adequate angle of slope.

As discussed earlier a unit of this type--even with these design features-- requires some pressure-part modification to achieve full load output if converted to coal or CWM firing. In this instance, these modifications consist of:

- Some horizontal convection surface respacing

- An upper furnace radiant superheater installation (to reduce furnace exit gas temperature)

- Burner respacing.

The cost of these items, although high, is not substantial when compared with total project costs or with the cost of replacement power purchased in the event of a derating.

Table 3 summarizes an economic evaluation of the conversion alternatives being considered. Several conclusions are evident from a detailed review of the table:

- As indicated previously, the cost of the boiler modifications necessary to avoid derating of a unit of this type is approximately 10 percent of total conversion costs and is thus, in this case, economically justifiable.

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- Both fuels present viable conversion options, even if only 50 percent of the accrued fuel savings are recoverable toward payback of capital investment.

- The total capital cost of a conversion to pulverized coal is significantly higher than conversion to CWM, primarily because of the expense of a coal yard.

- Based on the comparison of benefit-to-cost ratios of the conversion fuels considered, CWM is the more economically justifiable conversion option.

Foster Wheeler and its family of companies is dedicated to the commercialization of CWM as a boiler fuel, as evidenced by our participation in:

- Boiler conversion design studies

- Burner development

- Coal cleaning and slurry preparation

- Fuel-production plant design

- Small utility conversion demonstration.

Foster Wheeler views CWM as one of the most promising alternatives to foreign oil dependence while using one of the most abundant resources available in the Western Hemisphere.
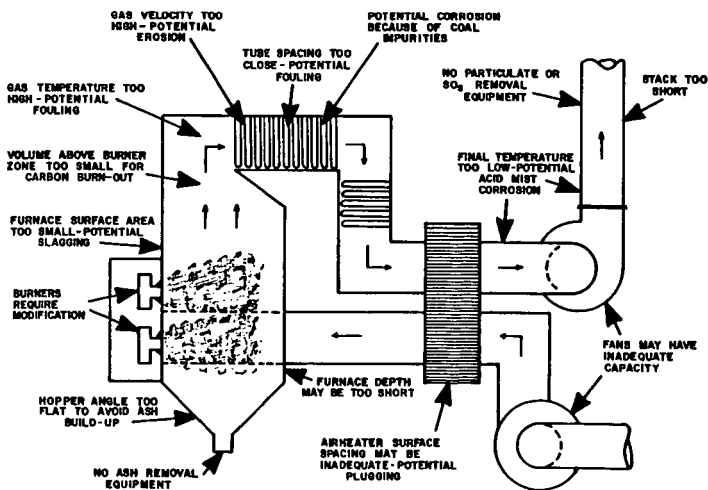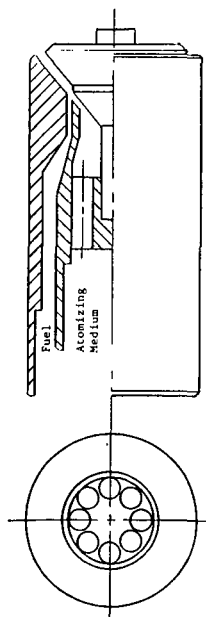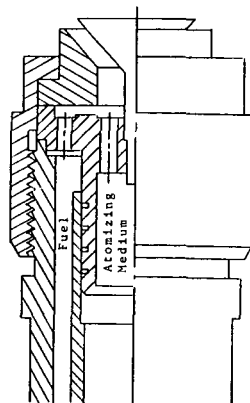

Figure 1 Potential Problem Areas in Retrofitting an Oil-Fired Furnace to CWF Firing

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Table 3 Conversion Economics Evaluation

Fuel	$ Million	
	Coal	CWM
Annual Fuel Costs	39.1	70.1
Annual Fuel Savings (vs. Oil)	67.4	36.4
Recoverable Portion of Savings	33.7	18.2
Levelized Annual Present Worth of Recoverable Savings	51.9	28.1
Capital Equivalent of Recoverable Savings	259.5	140.5
Conversion Costs		
Fuel System	96.4	9.3
Boiler Modification	4.7	2.3
Ash Systems	18.4	16.2
FGD System	41.7	41.7
Total	161.2	69.5
(w/o FGD)	(119.5)	(27.8)
Capital Payback Period, years	3.1	2.5
(w/o FGD)	(2.3)	(1.0)
Benefit-to-Cost Ratio	1.6:1	2:1
(w/o FGD)	(2.2:1)	(5.1:1)

Primary Air Refractory Throat

Secondary Air Refractory Throat

Stationary Swirler

Stabilizer

Secondary Air

Stationary Vanes

Slide Dampers

Primary Air

Windbox Front

Igniter

Cooling Air

Fuel Gun

Flame Detector

FIGURE 3   FORNEY CWF BURNER

Fuel

Atomizing Medium

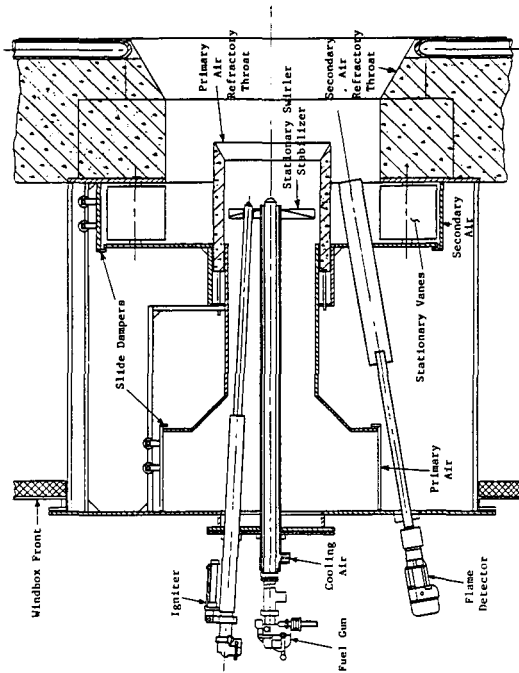Conical Y-Jet Atomizer

Fuel

Atomizing Medium
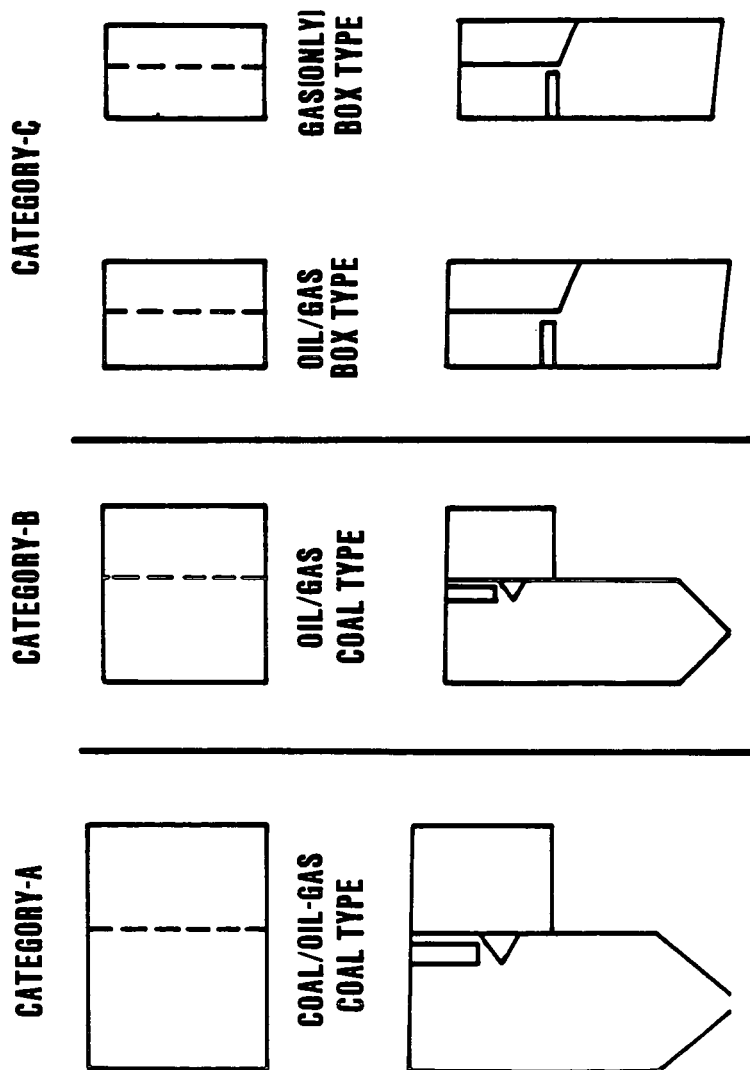
Conical Internal-Mix Atomizer

FIGURE 2   SPECIAL CONICAL ATOMIZERS

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Figure 4 Comparison Boiler-Fuel Configurations

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